The Operational Evaluation of the Navy's Globally Relocatable Tide Model (PCTides)

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Abstract **- The U.S. Naval Research Laboratory has developed a globally relocatable tide/surge forecast system. This system runs on a UNIX platform but was designed originally for PC-based use and is referred to as PCTides. The core of the system is a 2-dimensional barotropic ocean model. The model is forced with boundary conditions from a global tide model and uses surface winds and pressures (if available) and/or astronomical forcing. The global ocean bathymetry is a 2-minute global database developed by the Naval Research Laboratory. Atmospheric forcing from the Navy's global or regional models is provided through the METCAST system and used to generate real time, wind driven forecasts. PCTides output includes time series of tidal height deviations at each grid point of the model and time series of tidal height deviations at higher frequency (usually 10-12 minutes) at specified point locations. Barotropic tidal currents are also produced by the system.**

PCTides has successfully completed its operational evaluation performed by the Naval operational centers located in Norfolk, Virginia and San Diego, California. PCTides was run daily in real time to forecast tidal height deviations from regions along the east and west coasts of the United States. The model forecasts were compared to real time observations from the National Oceanic and Atmospheric Administration (NOAA) coastal tide gauges. Results from these evaluations showed an average amplitude error of 15 cm and a phase error of 30 minutes. Specific examples of PCTides hindcasts and forecasts for various areas will be presented and discussed.

I. INTRODUCTION

Over the past 3 years, the Naval Research Laboratory (NRL) has developed a globally relocatable tidal prediction capability that can run on either a PC or UNIX based system. This prediction system, call PCTides, has a 2-dimensional (2-D) barotropic ocean model as its core (Fig.1). PCTides uses this depth-integrated shallow water model to predict both the barotropic currents and sea level heights on or near continental shelves [1,2]. It contains a wetting and drying algorithm for the simulation of coastal flooding due to tides and/or storm surge. Surface winds, pressure and/or astronomical forcing drive this model. A global tide model, the Finite Element Solutions 95.1/2.1 (FES95.1/2.1) is used to provide tidal conditions at the open boundaries of the ocean model [3].

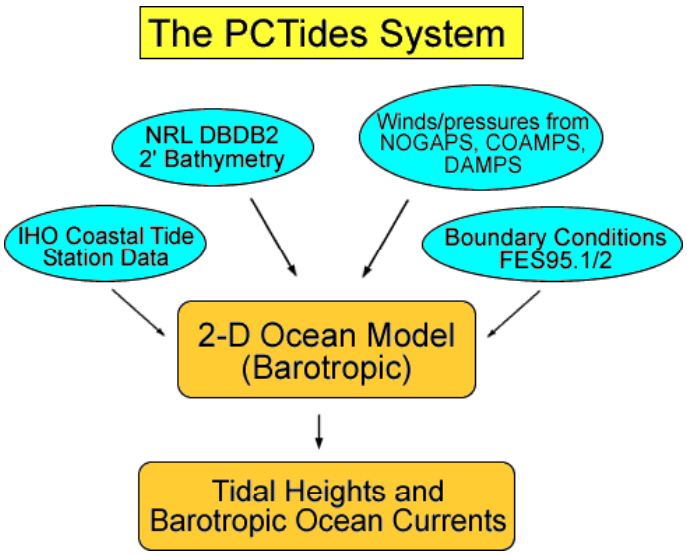

Fig.1. Schematic of the PCTides system.

All databases, except for the wind forcing, are internal to the PCTides system. These include: 1) bathymetry, a 2-minute global data base derived from a combination of the Navy's DBDBV data, the Smith and Sandwell dataset, the DAMEE North Atlantic data, the IBCAO Arctic data, as well as regional data sets from the Gulf of Mexico and Yellow Sea 2) the FES95.1/2.1 solutions and 3) tidal station data from the International Hydrographic Office (IHO) database. The IHO data is used for either model validation or for data assimilation.

In most applications of the system, winds from the Navy Operational Global Atmospheric Prediction System (NOGAPS) model [4], the Coupled Oceanographic and Atmospheric Mesoscale Prediction System (COAMPS) or the Distributed Atmospheric Prediction System (DAMPS) are available and therefore used. These fields are used daily at the operational centers and retrieved typically through the Navy's METCAST system.

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Tidal heights and barotropic ocean currents are the products of the PCTides system. The user has the option of pre-selecting station locations where high frequency (10-12 minute) tidal time series forecasts are produced. Stations are identified by latitude and longitude locations prior to the forecast. These time series are written to a file containing station information, date, time, tidal elevation, current speed and direction. The forecast may be viewed as a printed text file or plotted as a time series curve. In addition to the station forecasts, tidal elevations and currents are output at each model grid point at a pre-selected time interval with a minimum value of 30 minutes.

During the development and testing of PCTides, the system was evaluated against observations in several locations. Tidal height data was available for comparison in most of these locations. In a few select regions (Yellow Sea and Korea Strait), tidal current information was also available. The evaluation of PCTides forecasts to these observations gave us confidence in the product. In addition, PCTides was "beta-tested" at the Navy's operational center in Rota, Spain. Positive comments from the beta-test users, as well as the acceptable results from the model comparisons to the observations, allowed us to proceed to the next step, the operational evaluation of the model called the OPTEST.

From March through June 2001, the Naval Atlantic Meteorology and Oceanography Center (NLMOC) at Norfolk, Virginia conducted the operational evaluation of PCTides. A 48-hour forecast was generated each day using wind and surface pressure forcing from NOGAPS. The resultant tidal height fields from the model were evaluated against observations at selected points along the eastern coast of the United States.

During the same time period, the Naval Pacific Meteorology and Oceanography Center (NPMOC) at San Diego, California conducted an additional operational evaluation of PCTides. Again a 48-hour forecast was generated each day using wind and surface pressure forcing from NOGAPS/COAMPS. As before, the resultant tidal height fields from the model were evaluated against observations at select points along the western coast of the United States.

II. DISCUSSION

The evaluation of the PCTides forecast was performed by comparing the 48-hour model forecasts to the corresponding real time observations of the Mean Lower Low Water (MLLW) available from the NOAA website [5] at the pre-determined coastal stations. The NOAA observations were run through a 1-2-1 Hanning smoother several times to remove high frequency variability. Since tide models produce the tidal variation about the mean water level, an important aspect of this evaluation was an appropriate way to remove the mean from the observations. Although NOAA has a 19-year observational mean for each of the pre-determined stations, such a mean would probably not be available at every point of interest to the Navy. Therefore both centers approached the issue of removing the mean in the following way. A 2-day mean was computed from the data for every 48-hour period associated with the 48 hour forecast. The mean was then subtracted from the raw observations therefore removing the MLLW and resulting in a more realistic comparison between model amplitudes and observations.

At the end of the evaluation period, the model output was quantitatively compared to the NOAA observations. Statistics were calculated for each station's 0-24 hour forecast and 24-48 hour forecast over the entire OPTEST period by comparing model versus observed minimum and maximum tidal elevations. The following statistics were studied:

- AME - Absolute Mean Error of amplitude (meters)
- RMSA -Root Mean Square Error of amplitude (meters)
- MPD - Mean Phase Difference (minutes)
- RMSP - Root Mean Square Error of phase (minutes)

The pass/fail criteria were determined prior to the OPTEST evaluation period. The root mean square amplitude error of PCTides tidal elevation forecast vs. NOAA observed tidal elevation had to be less than 1.2 feet (0.365 meters). The root mean square phase error of PCTides peak tidal times versus NOAA's peak observation times must be less than 45 minutes.

NRL developed a website during the OPTEST where the model forecasts were displayed and compared to the NOAA observations. Each day's 48-hour forecast was displayed along with a plot of the 48-hour forecast from two days earlier with the NOAA observations overlaid. This allowed the OPTEST scientists to view the model/data comparison and develop confidence in the product.

A. U.S. East Coast evaluation

The U.S. East Coast evaluation focused on the Chesapeake Bay area (Fig. 2). A model domain was set up to cover this region using a grid resolution of 4.4 km and 68 x 141 grid points. A total of 8 stations were chosen and then compared to NOAA tidal observations during the same time period. The coastal stations included in the comparison were: Baltimore (39.15° N, 76.40° W), Solomon Island (38.32° N, 76.39° W), Windmill Point (37.62° N, 76.30° W), Sewell's Point (36.95° N, 76.33° W), Chesapeake (36.97° N, 76.11° W), Kiptopeke (37.17° N, 75.99° W), Lewes (38.78° N, 75.12° W), and Duck (36.18° N, 75.75° W).

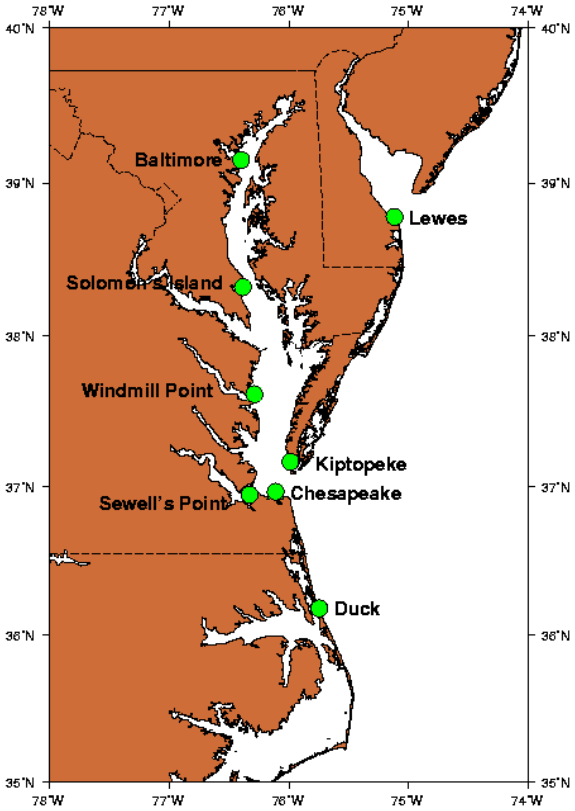

Fig. 2. Chesapeake model domain with NOAA observational stations indicated.

PCTides forecasts were run each day on a 1 GHz, Pentium III, Windows NT desktop PC. The model was cold-started each day and run for a 24-hour hindcast (with atmospheric forcing) and then continued the 48-hour forecast. Tests made prior to the operational evaluation determined that the 24-hour hindcast was the optimal spin up time for a typical PCTides forecast region. The model run time including the retrieval of atmospheric forcing took approximately 10 minutes. Figure 3 is an example of the forecast of tidal elevation from the OPTEST at the Chesapeake station.

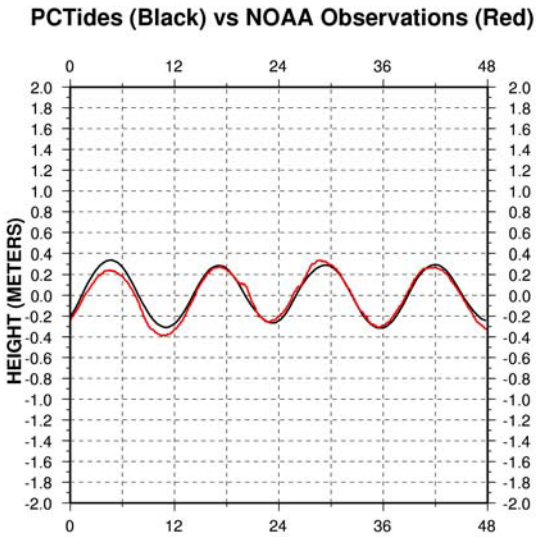

Fig. 3. 48-hour tidal height (meters) from PCTides (black line) vs NOAA Observation (red line) at the Chesapeake station (see Fig. 2). Plot valid for July 11, 2001 at 00Z.

Table 1 contains the statistics for all eight stations during the first 24 hours of each daily forecast. There were 3 stations that passed the amplitude criteria but failed the phase criteria (see highlighted columns on Table 1). The 3 stations that failed the criteria were Baltimore, Solomon Island and Windmill Point. In general, predictions for stations along the outer coast are more accurate than those stations located farther inland within the bay/estuary. The inland stations are more susceptible to the effects of wind and other meteorological effects than stations along the outer coast. Baltimore and Solomon Island stations are located in harbors sitting at the end of a long south-eastern fetch and therefore are extremely difficult to forecast correctly. Winds that blow along the length of the bay have been known to cause water levels to be 1-2 feet above or below the predicted tides. The NOAA Windmill station was positioned inside a river mouth. PCTides does not include river outflow, which could have added error during strong outflow events.

Table 1. First 24 hour forecast comparison
PCTides vs NOAA Observation Stations

Station	AME (m)	MPD (min)	RMSA (m)	RMSP (min)
Baltimore	0.28	-31.6	0.32	59.4
Solomon Island	0.10	-40.8	0.14	53.8
Windmill Point	0.08	68.6	0.11	69.2
Sewell's Point	0.09	20.1	0.12	20.8
Chesapeake	0.09	-12.4	0.12	23.7
Kiptopeke	0.09	-5.9	0.12	18.2
Lewes	0.21	2.4	0.24	14.4
Duck	0.10	-9.8	0.13	20.5

The mean phase difference (MPD) was calculated by subtracting the NOAA observation station data from the PCTides model forecast. Therefore a positive bias means that the model high or low tidal peak occurred after the observed NOAA peak. In six out of the eight pre-selected stations, the model's RMS amplitude error varied from the NOAA observations by less than 15 cm/sec. The other two station's RMS amplitude error varied less than 35 cm/sec. Five out of the eight modeled stations had RMS phase errors that varied less than 24 minutes when compared to the NOAA observations. The second 24-hour forecast period comparison was generally the same as the first 24-hour period and therefore will not be shown. Overall, PCTides performed very well, passing both phase and amplitude criteria in 5 out of the 8 stations for both the first and second 24-hour period comparison.

B. U.S. West Coast evaluation

Three regions were chosen for evaluation along the US West Coast: the southern California Coast, the southern coast of Alaska, and the Washington State/British Columbia waterways. The first domain, the southern California coast (Fig. 4), used a grid resolution of 17 km and 124 x 98 grid points. Only one station in this area was chosen and then compared to the NOAA tidal observation during the same time period. The station was located at the Scripps Institute pier (32.87° N, 117.27° W).

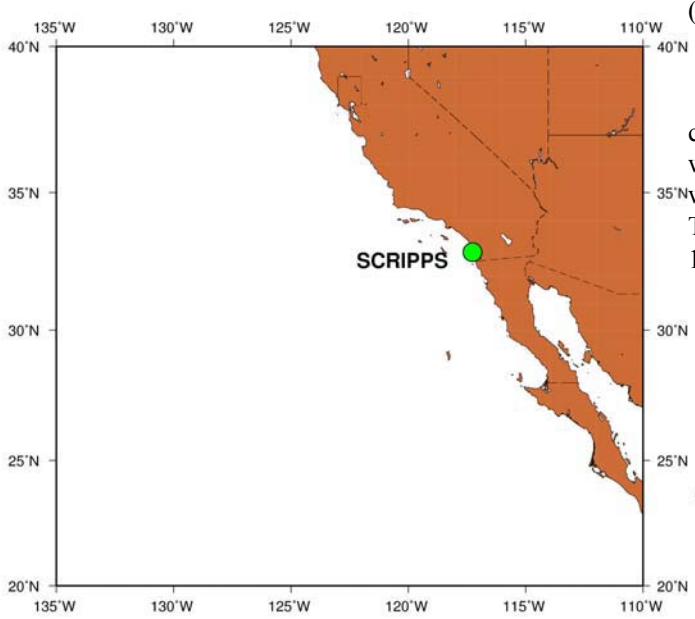

Fig. 4. Southern California model domain with the NOAA observational station indicated.

As in the east coast evaluation, the west coast evaluation was run each day on a 1 GHz, Pentium III, Windows NT desktop PC. Each of the three models was cold-started each day and run for a 24-hour hindcast (with atmospheric forcing) and then continued the 48-hour forecast. All three west coast evaluation regions were run using this spin-up method. The total model run time for the three areas, using either COAMPS (Southern California and Puget Sound area) or NOGAPS (Kodiak Island area) atmospheric forcing, took approximately 30 minutes. This 30 minute time frame also included the retrieval and processing of the atmospheric forcing. Figure 5 is an example of the forecast of tidal elevation from the OPTEST at the SCRIPPS station location.

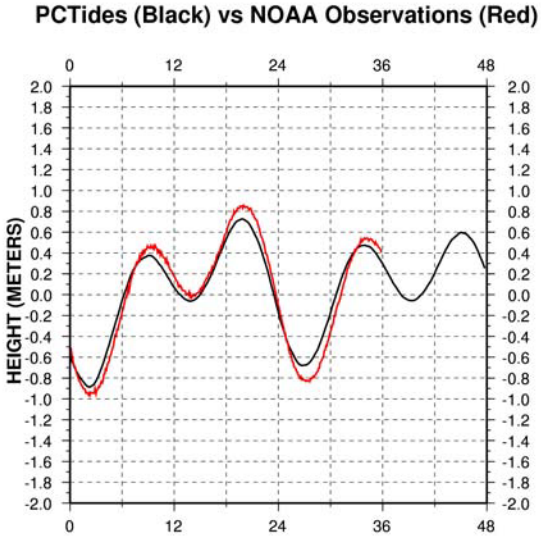

Fig. 5. 48-hour tidal height (meters) from PCTides (black line) vs NOAA Observation (red line) at the Scripps station (see Fig. 4). Plot valid for June 25, 2001 at 12Z.

The second domain covered the southern Alaska coast including Kodiak Island (Fig. 6). The grid resolution was 25.1 km and 117 x 79 grid points. Only one station was chosen and compared to the NOAA tidal observations. The station was located on Kodiak Island (57.71° N, 151.90° W).

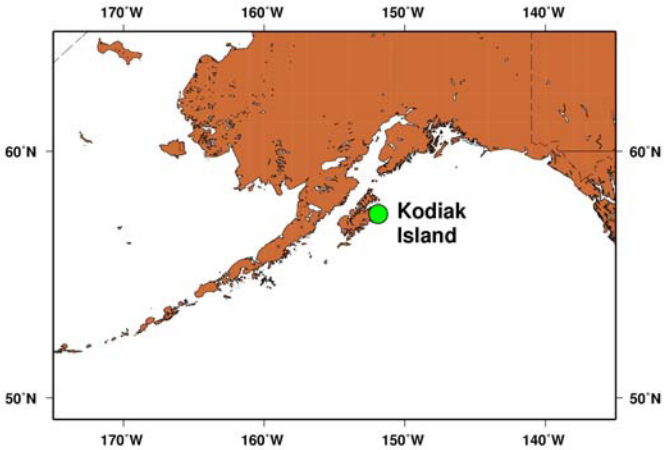

Fig. 6. Kodiak Island model domain with the NOAA observational station indicated.

The third domain covered the Strait of Georgia, the Strait of Juan DeFuca and the Puget Sound (Washington State) area (Fig. 7). The grid resolution was 2.7 km and 132 x 182 grid points. Two stations were chosen and then compared to NOAA tidal observations. The coastal stations included in the comparison were: Port Angeles (48.19° N, 123.43° W) and Seattle (47.55° N, 122.41° W).

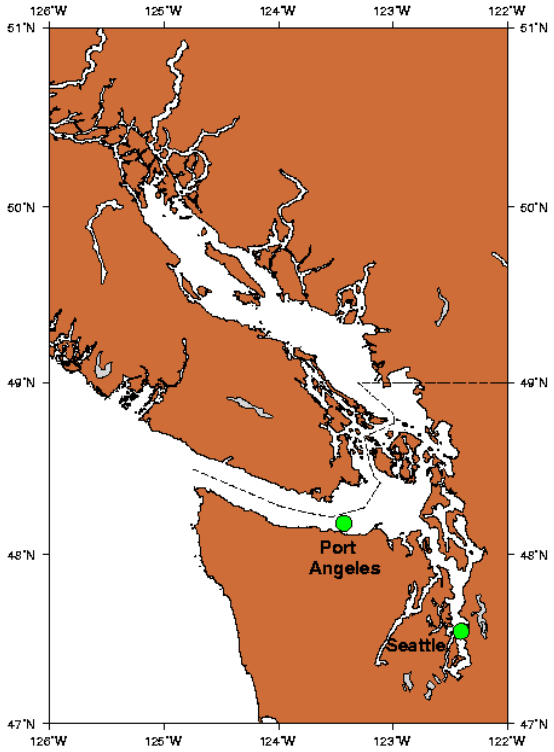

Fig. 7. Puget Sound (Washington State area) model domain with the NOAA observational stations indicated.

Table 2 contains the statistics for the four stations included as part of the west coast evaluation test during the first 24-hours of each daily forecast.

Table 2. First 24 hour forecast comparison PCTides vs NOAA Observation Stations

Station	AME (m)	MPD (min)	RMSA (m)	RMSP (min)
Scripps	0.10	0.65	0.12	24.28
Kodiak Island	0.22	26.05	0.26	32.62
Port Angeles	0.25	-7.73	0.32	25.52
Seattle	0.15	-29.83	0.18	31.09

During the evaluation along the western coast of the United States, all four stations passed the criteria for both amplitude and phase. The modeled RMS amplitude error of all four stations varied less than approximately 35 cm/sec. The modeled RMS phase error of all four stations varied less than 35 minutes from the NOAA observations. Although all stations passed the criteria, the evaluation revealed several sensitivities of the PCTides model. At the Kodiak Island station, the location was incorrectly inserted into PCTides, causing the forecast to be made for a location in 85 meters of water instead of one closer to the shore (the location of the NOAA observation). The location of the station must be carefully chosen and correctly entered into the model.

At the Scripps station, phase error was shown to be a function of the model's grid size. Typically grids used by PCTides should have a grid resolution of less than 10 km. In the southern California case, the operator chose a grid resolution of 17 km resulting in a phase error of 24 minutes. When a 5 km resolution grid was used over the same area, phase errors were only 5 minutes. The higher resolution grid allowed for better resolution of the bathymetry and coastline resulting in greater forecast accuracy. This grid resolution issue was also a factor at the Kodiak Island station. In that case, the grid resolution was coarse (25.1 km) and did not allow for accurate resolution of the bathymetry or accurate placement of the station. With this in mind, the user needs to create grids with resolution less than 10 km.

The second 24-hour forecast period comparison was generally the same as the first 24-hour period and therefore will not be shown. Overall, PCTides performed very well, passing the OPTEST criteria at all four stations for both the first and second 24-hour period comparison.

C. Improvements

Upon completion of the operational evaluation, each of the centers had an opportunity to make suggestions for system improvement based on their experience running the PCTides system. As a result of these comments, several changes were implemented in the final version of PCTides that was ultimately delivered to the Naval Oceanographic Office. A major concern of the operational centers was that PCTides did not have a convenient method of saving the model output plots to a file that could be easily distributed to the fleet users. Because of this, PCTides graphics were upgraded to save the model output in "gif" format, which can be posted to the center's website for distribution among users. Along with the ability to archive/save plots, the model output graphic package was upgraded to improve the general appearance of the plots.

During the past year, NRL developed a 2-minute global bathymetry data set (NRL DBDB2) based on the Navy's DBDBV data, the Smith and Sandwell dataset, the DAMEE North Atlantic data, the IBCAO Arctic data as well as regional data sets from the Gulf of Mexico and Yellow Sea. A major goal of this new database was to

improve the coastline and island representation and to improve coastline-bathymetry matching. The bathymetry used in the PCTides OPTEST was a 3-minute interpolated dataset based only on DBDBV 5-minute data and its available higher resolution bathymetry data. Comparisons of the 2-minute and 3-minute global data showed greater accuracy in the 2-minute data, particularly along coastlines and in shallow water. Therefore, PCTides was delivered using the new NRL DBDB2 bathymetry dataset.

Another modification to PCTides, suggested during the evaluation, added the capability for the user to input and use a high-resolution bathymetry dataset. This software has been added to the system as an option that is run outside of the PCTides main menu.

The following upgrade to PCTides was also a direct result of user input. Based on the fact that the model grid produces a rectangular grid estimation or representation of the coastline, station locations that are very near the coastline may fall on land. PCTides now includes an automated process that moves such a station to the nearest ocean (water) point that exists on the model grid and informs the user of this change before proceeding with the forecast.

III. CONCLUSION

Over the past 3 years, the Naval Research Laboratory (NRL) has developed a globally relocatable tidal prediction capability that can run on either a PC or UNIX based system. This prediction system, called PCTides, consist of a 2-dimensional barotropic ocean model driven by a combination of wind and atmospheric pressure fields and/or astronomical forcing. From March through June of 2001, the Navy operational centers at Norfolk, Virginia and San Diego, California conducted an operational evaluation of PCTides. The model made a 48-hour forecast each day including wind and surface pressure forcing from NOGAPS or COAMPS. The resultant tidal height fields from the model were evaluated against observations at selected points along the eastern and western coasts of the United States. In order to pass the evaluation, PCTides had to produce: 1) tidal heights that were less than 1.2 feet (0.365 meters) of the observed data and 2) tidal phases that were less than 45 minutes of the observed data. Overall, PCTides performed very well, as demonstrated in the evaluation, in which 18 out of the 24 statistical criteria were met. During July 2002, PCTides was delivered to the Systems Integration Division at the Naval Oceanographic Office, Stennis Space Center, Mississippi for the Navy's use as a relocatable tidal model.

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